Unheralded Teleportation Fidelity Improvement with Quantum Memory

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Abstract: Unheralded teleportations with Optical Bell State Measurements using SPDC sources are limited to 0.5 fidelity. Single photon emissions and non-destructive heralding from quantum memories overcomes this limit. ©2022 Massachusetts Institute of Technology.

1. Introduction

The development of quantum information networks — i.e., a system that can reliably move a quantum superposition such as a qubit over distances with minimal decoherence — are focused on entanglement distribution, with quantum state teleportation a primary use case. That is, a Bell State is distributed to two parties (Alice and Bob), and a local Bell State Measurement (BSM) between an unknown "user" state at Alice and one half of the distributed Bell State teleports the user state to Bob's half of the entangled pair (as shown in Fig. 1).

Photons are needed to distribute entanglement over long distances, but it is widely recognized that quantum memory banks will be needed for on-demand entanglement usage. However, current development efforts are mostly focused on using existing technology to validate system concepts and demonstrate initial capabilities. Herein we provide an analysis of fidelity (noise) issues from using legacy technologies for useful long-distance teleportation, and show the improvements from using the limited quantum memories available today.

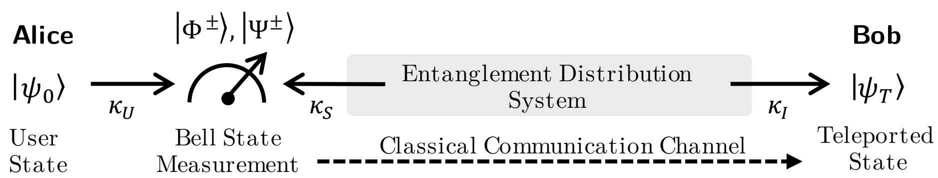

Fig. 1: Schematic for quantum teleportation using an entanglement distribution system. The baseline BSM is all optical, relying on coincidences. Quantum memory on the inputs of the BSM can significantly increase the fidelity of $|\psi_T\rangle$ to $|\psi_0\rangle$ for unheralded teleportation. κ_S, κ_I and κ_U are losses for the signal, ilder and user photons.

2. Current Approaches

The workhorse of entanglement distribution systems are spontaneous parametric downconversion (SPDC) sources, which generate maximally-entangled jointly Gaussian states. When two such sources (or one that is double pumped) are interfered at a beam splitter they can be used to generate Bell States. For example, a Sagnac interferometer source set to generate a polarization-entangled singlet state $\Psi^- = \frac{1}{\sqrt{2}}(|0\rangle_{S,H}|0\rangle_{I,V}|1\rangle_{I,H}|1\rangle_{S,V} - |1\rangle_{S,H}|1\rangle_{I,V}|0\rangle_{I,H}|0\rangle_{S,V})$ would output

$$|\psi\rangle = \sum_{n=0}^{\infty}\sum_{m=0}^{\infty}(-1)^n\sqrt{\frac{N_0^{n+m}}{(N_0+1)^{n+m+2}}}\,|n\rangle_{S,H}|n\rangle_{I,V}|m\rangle_{I,H}|m\rangle_{S,V}\,, \tag{1}$$

where S and I are the signal and idler modes, H and V are horizontal and vertical polarizations, and N_0 is the mean number of photons per mode [1]. For $N_0 \ll 1$, the likelihood of measuring k photon pairs is $\sim N_0^k$, the amplitudes of higher-order terms rapidly decay, and this approximates a weighted superposition of vacuum and Ψ^-.

In the teleportation schematic in Fig. 1, the signal photon goes to Alice while the idler photon goes to Bob. At Alice, a Bell State Measurement of the signal with her qubit $|\psi_0\rangle$ "teleports" it onto the idler at Bob (modulo a potential single photon operation). An Optical Bell State Measurement (OBSM), which relies on two-photon interference at a beam splitter, is generally used for the teleportation [2].

In a laboratory experiment this can be done with high fidelity by heralding (detecting) the idler at Bob. However, an entanglement distribution system needs high fidelity without destroying the teleported state. As we will show, to do that with an SPDC-based entanglement sources and an OBSM requires either a non-destructive herald, or the user to have a true single-photon source; otherwise the fidelity is limited to 0.5.

To start, we assume that we are teleporting a pure state so that the fidelity reduces to [3]

$$F(\hat{\rho}_T, |\psi_0\rangle) = \langle\psi_0|\,\hat{\rho}_T\,|\psi_0\rangle\,, \tag{2}$$

where $\hat{\rho}_T$ is the density operator of the teleported state (heralded only by the BSM). This is equivalent to the likelihood of a measurement device set to measure $|\psi_0\rangle$ detecting it (on a pulse that had a BSM detection). When using SPDC sources two photons can arrive at one port of the OBSM (and none at the other), the device can still "detect" a Bell State, and the fidelity is degraded. While we attempt to generate the user state $|\psi_0\rangle = \alpha\,|01\rangle + \beta\,|10\rangle$, for our baseline we assume SPDC-like statistics with N_U mean photons per mode.

Under some basic simplifying assumptions ($N_0 \ll 1, N_U \ll 1, \kappa_s \ll \kappa_u$) the Fidelity of the teleported state to the initial state is well approximated by

$$F(\hat{\rho}_T, |\psi_0\rangle) \approx \frac{\kappa_I\,[\Pr(C) + (N_S/2)\Pr(U) + (1-\kappa_I)\Pr(E)]}{\Pr(C) + \Pr(U) + \Pr(E)}, \tag{3}$$

where C is a true coincidence, E is a double detection caused by the entanglement source, and U is a double detection caused by the user source. The relative likelihood of these events are $\Pr(C) \propto 2N_0\,\kappa_S N_U\,\kappa_U$, $\Pr(E) \propto N_0^2\,\kappa_S^2$, and $\Pr(U) \propto 4|\alpha|^2|\beta|^2 N_U^2\,\kappa_U^2$. The fidelity is maximized when $\kappa_I = 1$ and $\Pr(U) = \Pr(E)$, and thus $F(\hat{\rho}_T, |\psi_0\rangle) \lesssim 1/2$.

High fidelity can be recovered by heralding on the idler, which suppresses user-source doubles. Given idler hearalding, we also note that high fidelity requires approximately equal input powers to the OBSM, so that the achievable rate is $\propto \kappa_S^2$. This has lead to proposals for the entanglement distribution system that has two sources, one near each end node, and a BSM to do an entanglement swap between them, so as to minimize κ_S. For a satellite system, this means a source at each ground station and a BSM on the satellite in a "dual uplink" configuration.

3. Single Photons and Quantum Memory

High fidelity teleportation with OBSMs requires suppression of multi-pair events. A non-destructive herald at Alice, Bob, or both can help with this. Alternatively, a single-photon user source can increase flux (and thus coincidences) without increasing noise from doubles. In this limit, the fidelity (for $\kappa_I \to 1$) simplifies to $F(\hat{\rho}_T, |\psi_0\rangle) \approx 1/(1 + \frac{N_0\,\kappa_S}{2N_U\,\kappa_U})$, which can be made arbitrarily close to unity (at the cost of user-photon efficiency).

One promising technology for both single photon emission as well as non-destructive heralding is color-center vacancies in diamond [4]. When used as an emitter, single photons (entangled with an electron spin) can be deterministically emitted, allowing for OBSM usage with high fidelity. In an alternative configuration, the color center is in a cavity whose reflectance is highly coupled to the the electron spin. This enables transference of a qubit from a photon to the electron spin before detecting the photon, allowing for a heralded read-in. A Bell State Measurement can be performed between two subsequent photons, enabling on-demand teleportation [5]. Additionally, this approach allows for much more efficient use of the user's photon — it is only sent in after the entanglement has been read-in and heralded. One drawback is that the natural bandwidth of the color center's photonic interaction is much narrower than the bandwidth of typical SPDC sources, making compatibility challenging.

While large banks of quantum memory are needed to implement on-demand entanglement usage, high fidelity, user-state-efficient teleportation systems can be demonstrated in the near term using single quantum memories that are becoming available today. By using a memory for the BSM we do not need to wait for coincidences, so every photon is used, and we do not have to worry about doubles from an SPDC source limiting fidelity.

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